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On the Polarizing Interstellar Dust

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Summary. An interpretation for the parameter k in Serkowski's normalization for the linear polarization is given in relation to a changing alignment model for the interstellar grains. Present observations indicate a correlation between k and dust size changes along the line of sight. Linear and circular polarization measurements seem to be consistent with an absorbing material for the polarizing component of the interstellar grains. Polarization position angle observations are also analyzed.

Key words: interstellar grains — polarization of stellar light

I. Introduction

The interstellar linear polarization presents a rough regularity in its wavelength dependence for different regions of the sky. Serkowski (1971) fits the ensemble of many observations by an empirical formula:

$$P(\lambda)/P_m = \exp\{-k\ln^2(\lambda_m/\lambda)\} \tag{1}$$

where $P(\lambda)$ is the degree of linear polarization at the wavelength λ; λ_m is the wavelength at which the maximum polarization, P_m, occurs; and $k \simeq 1.15$ is a constant, the same for all stars.

The physical significance of P_m and λ_m is clearly indicated by Coyne *et al.* (1974) and Serkowski *et al.* (1975). P_m is related to the column density and to the polarizing properties of the interstellar grains. λ_m is, for a given material, an indicator of the characteristic dimension of the dust.

The remaining parameter, k, is not easily related to the physical conditions of the polarizing agents. In the twofold normalized picture (1) of the wavelength dependence, it is a measure of the sharpness of the curve: increasingly smaller values of k give increasingly flattened curves. The constant value of $k=1.15$, estimated by Serkowski, gives the best fit for the set of stars considered as a whole, but it does not yield the best representation of the wavelength dependence for each star. Better agreement is, of course, obtained computing λ_m, P_m and k from the system of Eq. (1) corresponding to the set of observed $P(\lambda)$ for each star. The different values of k thus obtained imply differences in the shape of the $P(\lambda)/P_m$ versus λ_m/λ curves. Proceeding in this way we attain, for extreme cases: $k=1.47$ for HD 183143 and $k=0.19$ for HD 22253, as shown in Table 4. Each of Figs. 1 and 2 shows both observational and theoretical polarizations, the latter for $k=1.15$ and for the values mentioned above. The total squared deviations (observed minus theoretical) for each star are smaller by a factor of 5 to 10 when k takes on the appropriate value for each star. These departures could be due to several phenomena. The experiment errors seem not to be big enough to explain them. They could be due to dissimilarities in composition, shape, dimension, or alignment of the interstellar grains in the several regions of the Galaxy. The definite circular polarization of interstellar origin measured in the light of some stars (Kemp and Wolstencroft, 1972; Martin, 1974; Stokes *et al.*, 1974; Serkowski *et al.*, 1975) and the rotation of the position angle of linear polarization with wavelength are also constraints to be taken into account in the explanation of these peculiarities in the linear polarization.

Circular polarization of interstellar origin can arise from the effect of a polarizing cloud on lineary polarized radiation from a backround source (van de Hulst, 1957) or by a changing orientation of the grains along the path (Serkowski, 1962). A multiple cloud model with differing particle sizes was already suggested by Treanor (1963) and Coyne and Gehrels (1966). Recently, Kemp and Wolstencroft (1972) and Martin (1974a, b) analyzed such a model quantitatively. Martin studied grains with a constant index of refraction in the visible spectral range. He concluded that the imaginary part of the complex index of refraction must be nearly zero if its real part is about 1.5, supporting the idea of a dielectric nature for the grains.

In order to find an eventual correlation between k and some property of the interstellar dust, one has to make some reasonable assumption about the nature of the grains. That some correlation seems to exist emerges

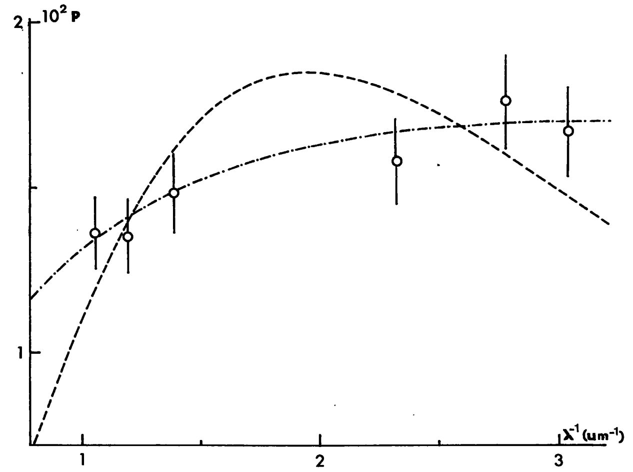

Fig. 1. Wavelength dependence of linear polarization of HD 22253. Points and error bars are observations from Coyne and Gehrels (1966). Dash lines: Eq. (1) for $k=1.15$. Dash and dot lines: Eq. (1) for $k=0.19$

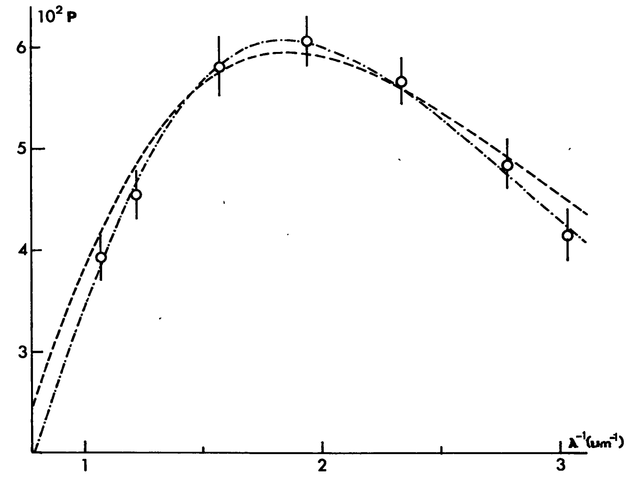

Fig. 2. Wavelength dependence of linear polarization of HD 183143. Points and error bars are observations from Coyne and Wickramasinghe (1969). Dash lines: Eq. (1) for $k=1.15$. Dash and dot lines: Eq. (1) for $k=1.47$

from the observations, as will be shown in section III. We also study the compatibility of the selected material in regard to circular polarization measurements.

We chose magnetite (Fe_3O_4) as the grain material because it is a possible ferromagnetic candidate. This was earlier suggested by Spitzer and Tukey (1951) in their analysis of the evaporation of atoms from the dust in the interstellar medium. Grains of magnetite can also be formed by condensation of a cooling gas of cosmic composition. Larimer (1967), studying the condensation of the elements under the above conditions, found out Fe_3O_4 is the iron oxide able to condense at temperatures below 400 °K. Other arguments are given by Huffman and Stapp (1973) who measured the optical constants of this material in the spectral range $0.5 < \lambda^{-1} < 12\ \mu m^{-1}$. Platelet grains of magnetite were considered by Shapiro (1975) in a model which can account for the observed wavelength dependence of linear and circular interstellar polarization.

In the next section theoretical considerations on the proposed model are given. Interpretation of observations is described in Section III, while conclusions are presented in IV.

II. Theoretical Considerations

Let us assume the existence of two clouds in the line of sight to some star. It is supposed that the dust consists of smooth circular cylinders composed of magnetite, with length ten times the radius. The alignment of the grains is that of a picket fence, with the grains' longest axis normal to the line of sight.

The assumption of a perfect static alignment permits a simple mathematical treatment of the model. It should be true for very dense clouds if there is an effective increase of its magnetic field during the evolutive contraction, as suggested by Verschuur (1969). However, the difference between such an alignment and the one of Davis-Greenstein is not qualitative in relation to the linear polarization dependence (Greenberg, 1968). Our results would be changed at most in the required grain number to fit the data.

The grains are supposed to be smooth circular cylinders. Experimental measurements (Landaberry *et al.*, 1974) of the linear polarization produced by magnetically oriented chains of magnetite grains showed that this is a sound approximation to the real particles. Such conglomerates should be a consequence of multiple coagulations of particles in their sources, as suggested by Lefèvre (1974).

A single size of the grains, or a narrow distribution for them, is assumed for each cloud. Our conclusions would remain essentially inaltered if a more realistic distribution of sizes is supposed.

Following Serkowski (1962), the set of Stokes parameters of the light reaching us can be written as:

$$\begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix} = \begin{pmatrix} \Sigma_1\Sigma_2 + \Sigma'_1\Sigma'_2 \cos 2\Delta\phi \\ \Sigma_1\Sigma_2 + \Sigma'_1\Sigma'_2 \cos 2\Delta\phi \\ -\Sigma'_1\Sigma_2^* \sin 2\Delta\phi \\ \Sigma'_1\Sigma'_2{}^* \sin 2\Delta\phi \end{pmatrix} \begin{pmatrix} I_0 \\ 0 \\ 0 \\ 0 \end{pmatrix} \tag{2}$$

where the Σ's are functions of the extinction and phase retardation cross sections and number densities of the grains in each cloud, with $\Delta\phi$ being the angle between the alignment direction of the two clouds. The indices correspond, respectively, to the first and second cloud, and $(I_0, 0, 0, 0)$ are the Stokes parameters of the unpolarized stellar light.

Equation (2) can be understood as arising from a transformation matrix for the Stokes parameters for light which has passed through a linear medium [see, for instance, van de Hulst (1957), p. 44]. The matrix elements can be related to the grains' cross sections via

Table 1

						$k=1.15$					Observations$^{b)}$	
HD	Other	Sp.	V	E_{B-V}	m–M	$\lambda_m{}^{a)}$ (μm)	$P_m{}^{a)}$ (%)	λ_m (μm)	P_m (%)	k	lin.pol.	circ.pol.
147165	σ Sco A/B	B 1–III	2.89	0.41	6.1	0.54	1.63	0.52	1.63	1.12	(1)	(2)
147889	−24 12684	B 2–V	7.89	1.12	7.0	0.81	4.07	0.79	4.13	1.30	(3)	(4)
204827	+58 2272	B 0–V	7.95	1.11	8.8	0.48	5.50	0.43	5.62	0.96	(3)	(4)

[a]) Taken from Coyne *et al.* (1974).

[b]) (1) Coyne and Gehrels (1966). (2) Kemp and Wolstencroft (1972). (3) Serkowski *et al.* (1969). (4) Serkowski *et al.* (1975).

van de Hulst's forward scattering approximation (van de Hulst, 1957, p. 32; Serkowski, 1962, p. 307). In this way, it can be seen that, for instance, for the first cloud:

$$\Sigma_1 = \frac{1}{2}(A_l^2 + A_r^2 + B_l^2 + B_r^2)$$

$$\Sigma_1' = \frac{1}{2}(A_l^2 - A_r^2 + B_l^2 - B_r^2)$$

$$\Sigma_1^* = A_r A_l + B_r B_l$$

$$\Sigma_1'^* = A_r B_l - A_l B_r$$

where

$$A_i = 1 - \frac{1}{2} C_i n_1$$

$$B_i = \frac{1}{2} C_i^* n_1\,, \qquad i = l, r$$

with n_1 standing for the column density and axes $\boldsymbol{l}$ and $\boldsymbol{r}$ such that $(\boldsymbol{r} \times \boldsymbol{l})$ indicates light propagation direction. The C_i and C_i^* represent the grains' cross sections for extinction and phase lag, respectively.

We can gain better insight into Eq. (2) considering a situation where we can disregard terms of the order of $(nC_i)^2$. In such a case we see that Σ'^* express linear birefringence and Σ' denote linear dichroism. It is seen that, from Eq. (2), circular polarization arises as a combination of linear dichroism of the first cloud with the linear birefringence of the second one, together with a change in the grains' alignment direction along the path.

The extinction and phase retardation cross sections are easily computed from Mie's theory for infinite cyclinders (van de Hulst, 1957) as functions of the radius a_i of the grains contained in cloud i. Assuming a value a_i and a column density n_i, we can compute the values of the Σ's for each wavelength λ.

The observational data to be fitted is:

$$P(\lambda) = \{Q^2(\lambda) + U^2(\lambda)\}^{1/2}/I(\lambda),$$

the degree of linear polarization;

$$C(\lambda) = V(\lambda)/I(\lambda),$$

the circular polarization; and

$$\Delta\theta(\lambda) = \theta(\lambda) - \theta(\lambda_0),$$

the rotation of the position angle, where

$\theta(\lambda) = \dfrac{1}{2}\,\mathrm{arctg}\,\{U(\lambda)/Q(\lambda)\}$ and λ_0 is an arbitrarily chosen wavelength.

It can be shown that the shapes of $P(\lambda)$ and $C(\lambda)$ are nearly independent of n_1 and n_2, provided n_1/n_2 is kept constant. $P(\lambda)$ is proportional to $n_1 + n_2$. The wavelength for which $P(\lambda)$ is maximum, λ_m, is a function of a_1, a_2 and n_1/n_2. If we take $a_1 = a_2 = a$, the value of λ_m goes up with increasing a⁽¹⁾.

$C(\lambda)$ is zero for $\Delta\phi = j\pi/2$⁽¹⁾, $j = 0, 1, 2, \ldots$, and has a single zero at $\lambda = \lambda_c \simeq \lambda_m$ in the range $1 < \lambda^{-1} < 3\,\mu\mathrm{m}^{-1}$ for other values of $\Delta\phi$. λ_c depends on a_2⁽¹⁾, increasing with increasing a_2. λ_c is approximately equal to the wavelength where the polarization produced by the second cloud is maximum.

$\Delta\theta(\lambda)$ is shape dependent on a_1 and a_2 but slightly dependent on n_1 and n_2. It is zero for all λ if $a_1 = a_2$⁽¹⁾. This is also the case if $a_1 \neq a_2$ but $\Delta\phi = j\pi/2$.

III. The Observational Data

We have selected three stars with measured $P(\lambda)$, $C(\lambda)$ and $\Delta\theta(\lambda)$, all free of intrinsic polarization. Two of them, HD 147889 and HD 204827, have widely different curves of $P(\lambda)$. They were indicated (Serkowski *et al.*, 1969) as extreme cases of difficult theoretical fit with a single material grain. Both have k values which differ from 1.15 (see Table 4). The third one, HD 147165, is an intermediate case. The work of Hobbs (1969) shows in the line of sight to this star a structure of three main clouds of Na I, two of them strongly predominant over the other. If there is some correlation between sodium concentrations and dust clouds, this may indicate some validity of the assumed model for HD 147165 with respect to the number of clouds. There are no similar observational data for the other two selected stars.

The observational data for the three stars is shown in Table 1. Its first eight columns reproduce information given by Coyne *et al.* (1974). Columns 9, 10 and 11 indicate the computed values of λ_m, P_m and k, obtained by solving the systems of Eq. (1) by least squares for the

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(1) These are general properties independent of the grain species.

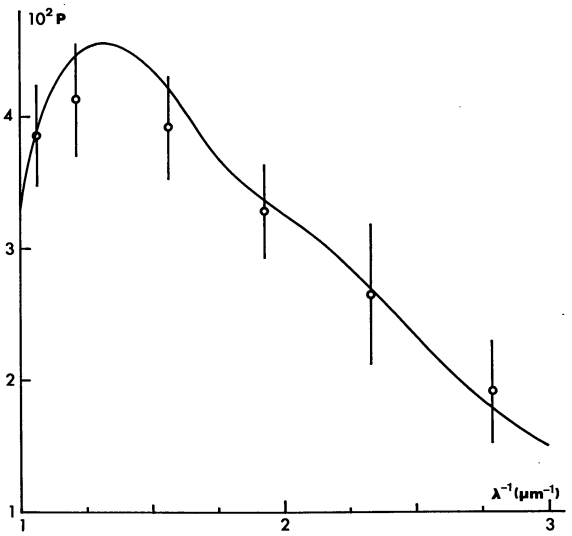

Fig. 3. Wavelength dependence of linear polarization of HD 147889. Points and error bars are observations from Serkowski *et al.* (1969). Solid line stands for computed polarization

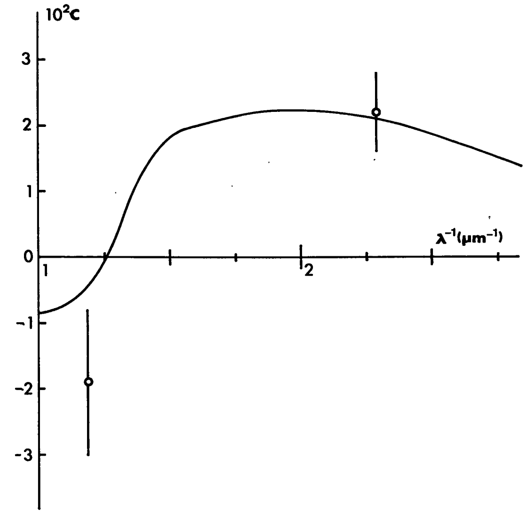

Fig. 4. Wavelength dependence of circular polarization of HD 147889. Points and error bars are observations from Serkowski *et al.* (1975). Solid line stands for computed polarization

three unknowns. It can be verified that λ_m, P_m and k so obtained fit the observational data much better than the ones which arise from a prefixed $k=1.15$. The difference between λ_m so determined and the one given by Coyne *et al.* (1974) imply a variation of the expected effective grain size in each case. In general, however, this dimension does not reflect actual grain sizes along the line of sight.

The results of our computations together with the observational points are shown in Figs. 3 through 8 for the three selected stars. Values of size, densities and $\Delta\phi$ corresponding to these figures are shown in Table 2. It also gives $\eta=(a_>/a_<)-1$, $a_>$ and $a_<$ being respectively the greatest and smallest values of a_1 and a_2, as a measure of grain size change along the path. The values of k are from Table 1.

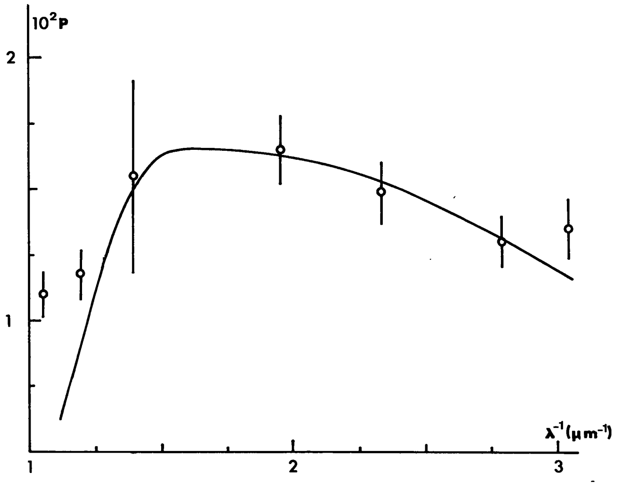

Fig. 5. Wavelength dependence of linear polarization of HD 147165. Points and error bars are observations from Coyne and Gehrels (1966). Solid line stands for computed polarization

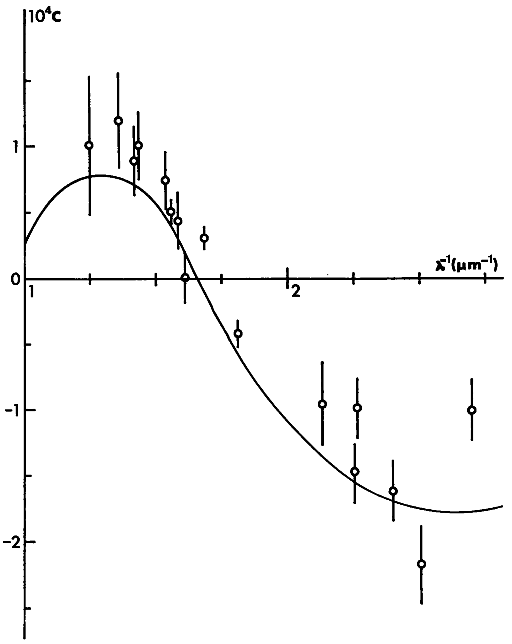

Fig. 6. Wavelength dependence of circular polarization of HD 147165. Points and error bars are observations from Kemp and Wolstencroft (1972). Solid line stands for computed polarization

It can be seen that a reasonable agreement for $P(\lambda)$ and $C(\lambda)$ is obtained in all cases. For HD 147165 and HD 204827, $P(\lambda)$ predicted is somewhat lower than the observations for $\lambda^{-1}<1.25\,\mu\mathrm{m}^{-1}$. However, this could be improved by refining some aspects of the model, such as considering a size distribution and another alignment mechanism. On the other hand, these could contribute to veil the significance we looked for.

η is a measure of the absolute difference between the size of the grains in one cloud and the other. It can be seen

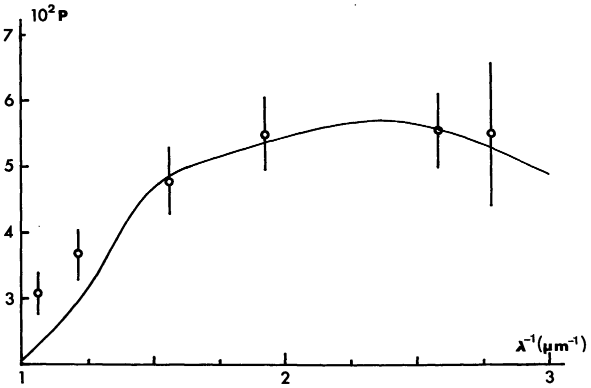

Fig. 7. Wavelength dependence of linear polarization of HD 204827. Points and error bars are observations from Serkowski *et al.* (1969). Solid line stands for computed polarization

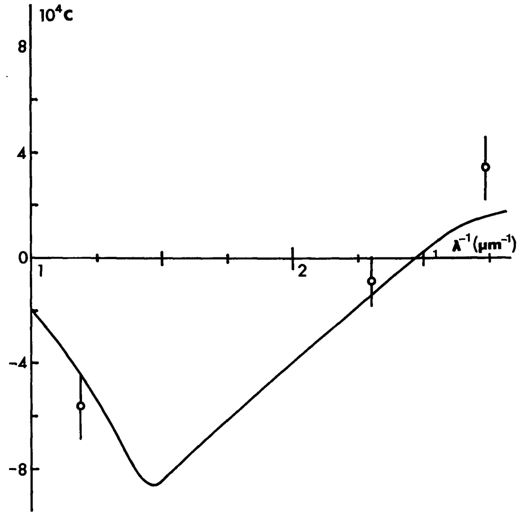

Fig. 8. Wavelength dependence of circular polarization of HD 204827. Points and error bars are observations from Serkowski *et al.* (1975). Solid line stands for computed polarization

Table 2

HD	a_1 (Å)	a_2 (Å)	$10^{-7} n_1$ (cm^{-2})	$10^{-7} n_2$ (cm^{-2})	$\Delta\phi$ (°)	η	k
147889	570	570	3.0	3.0	30	0.00	1.30
147165	270	370	14.0	7.0	−70	0.37	1.12
204827	420	200	7.0	56.0	40	1.10	0.96

Table 3

HD	$\Delta\phi = \|\theta^1 - \theta^2\|$ (deg)		Ref.	Notes
	Computed	Observed		
147889	0.0	1.1	(1)	$^1 = U$; $^2 = G$
		1.4	(2)	$^1 = U$; $^2 = V$
147165	9.6	2.8	(3)	$^1 = U$; $^2 = G$
		4.3	(2)	$^1 = U$; $^2 = V$
		6.1	(4)^{a})	$^1 = U$; $^2 = G$
		7.9	(4)^{b})	$^1 = U$; $^2 = G$
204827	7.0	1.0	(1)	$^1 = U$; $^2 = G$

References:
(1) Serkowski *et al.* (1969).
(2) Serkowski (1968).
(3) Gehrels and Silvester (1965).
(4) Coyne and Gehrels (1966).
^{a}) All observations combined.
^{b}) Observations during 1965.

that a high value of k corresponds to a small η and vice-versa. This is easily understandable, remembering that a small value of k in Eq. (1) implies a "flat" $P(\lambda)/P_m$ versus λ_m/λ curve. The same happens with the distribution of observational points in the plane $P(\lambda) - \lambda^{-1}$, $P(\lambda)/P_m$, when the particle sizes in one and another cloud are very different. Thus, a star for which k is high must be seen through clouds with $a_1/a_2 \simeq 1$, and a small k must correspond to radii $a_1 \neq a_2$. So, the value of k that best fits $P(\lambda)$ for a particular star should be an estimator of the discrepancy among particle sizes along the line of sight.

This seems also to be consistent with Martin's (1974b) calculated using dielectric grains for HD 147165. He finds the data to indicate a value of ~ 1.1 for the ratio of λ_m of the second and first clouds, respectively. In our case, this ratio is ~ 1.15. Therefore, for both metallic and non-absorbing particles, the small difference in grain sizes for σ Sco is coherent with $k = 1.12$ (Table 4).

In Table 3, a summary of computed and measured position angle rotations is shown. For HD 147889 and HD 147165 some qualitative agreement is obtained, while for HD 204827 even this is not attained. The uncertainty of the measurements prevent an appraisal of the model with regard to $\Delta\phi(\lambda)$. However, a statistical view of the subject should have more sense.

Table 4 lists all the stars more distant than 250 pc ($m - M > 7.0$) for which both linear and circular interstellar polarizations have been published up to now. In Columns 2 and 3, P_m and λ_m, taken from Coyne *et al.* (1974), are listed. Columns 4, 5 and 6 show P_m, λ_m and k computed in the way previously described. Column 7 gives the measured rotation of the polarization position angle for each star. References to the observational data are also listed. Single measurements of $\Delta\phi$ are not taken into account. Linear polarization observations that furnish the highest number of wavelength bands are used where more than one determination exists. It can be seen that stars with $k \gtrsim 1.00$ present small values of $\Delta\phi$ and vice-versa. The coefficient of correlation between k and $\Delta\phi$ is -0.68. This result seems to support our previous interpretation in regard to the relation between k and η, remembering that $\Delta\theta(\lambda) = 0$ for $a_1 = a_2$ (high k) and $\Delta\phi(\lambda) \neq 0$ when $a_1 \neq a_2$ (small k) for stars for which $C(\lambda) \neq 0$. This result is independent of the assumed material for the grains.

The possibility of magnetite as a constituent of the polarizing dust can be tested with respect to the inter-

Table 4

HD or other	$k=1.15$[a])		P_m	λ_m	k	$\vert\theta^G-\theta^U\vert$	Observations	
	P_m (%)	λ_m (μm)	(%)	(μm)		(deg)	lin.pol.	circ.pol.
24431	2.16	0.50	2.00	0.24	0.16	4.0	(1)	(2)
22253	1.85	0.51	1.70	0.31	0.19	9.0	(1)	(2)
207260	1.58	0.52	1.60	0.39	0.53	1.0 (4.6[b]))	(1)	(3)
36371	2.18	0.53	2.08	0.50	0.87	5.5/4.9	(1)/(10)	(2)
VI Cyg 12	9.61	0.45	9.92	0.41	0.90	3.0[c])	(4)	(5)
21389	3.77	0.51	3.68	0.49	0.92	0.8[c])	(1)	(2)
204827	5.50	0.48	5.62	0.43	0.96	1.0	(6)	(5)
183344	2.76	0.53	2.75	0.55	0.98	0.9[d])	(5)	(3)
43384	2.98	0.53	2.93	0.55	1.00	0.3/0.7[c])	(6)/(7)	(2)
198478	2.74	0.53	2.74	0.50	1.00	0.7	(1)	(3)/(8)
154445	3.63	0.55	3.52	0.54	1.14	0.7	(9)	(3)/(8)
23675	3.01	0.52	2.96	0.50	1.16	1.8	(9)	(2)
17378	4.55	0.54	4.58	0.54	1.25	1.0	(7)	(2)
13267	4.01	0.53	4.08	0.53	1.29	1.3	(7)	(3)
147889	4.07	0.81	4.13	0.79	1.30	1.1/1.4	(6)/(11)	(5)
216411	2.73	0.52	2.75	0.51	1.40	0.7	(10)	(5)
183143	5.94	0.54	6.06	0.54	1.47	0.1/0.0[c])/0.3[d])	(9)/(7)/(5)	(3)/(5)

[a]) Taken from Coyne *et al.* (1974).

[b]) Observations during 1965.

[c]) $\Delta\theta=|\theta^B-\theta^G|$.

[d]) $\Delta\theta|\theta^U-\theta^V|$.

References:

(1) Coyne and Gehrels (1966).
(2) Martin (1974).
(3) Stokes *et al.* (1974).
(4) Kruszewski (1971).
(5) Serkowski *et al.* (1975).
(6) Serkowski *et al.* (1969).
(7) Coyne (1974).
(8) Kemp and Wolstencroft (1972).
(9) Coyne and Wickramasinghe (1969).
(10) Coyne and Gehrels (1967).
(11) Serkowski (1968).

stellar iron abundance. We must have:

$$I=(\mathrm{H})A_{\mathrm{Fe}}>M=10\pi\varrho_m\frac{m_i}{m_m}\frac{\sum_i a_i^2 n_i}{r},\qquad i=1,2$$

where $(\mathrm{H})=1.67\times10^{-24}\,\mathrm{g\cdot cm^{-3}}$ is the interstellar hydrogen density; $A_{\mathrm{Fe}}=2.2\times10^{-3}$ is the iron mass abundance; $\varrho_m=5\,\mathrm{g\cdot cm^{-3}}$ is the density of solid magnetite; $m_i/m_m=0.7$ is the mass fraction of iron in the magnetite and r is the star distance.

Table 5 shows the fraction M/I of interstellar iron that must be under the form of $\mathrm{Fe_3O_4}$, for each one of the three considered stars. The required iron for polarizing magnetite grains in the directions of all three considered stars is within the limit imposed by universal abundances in the interstellar medium. This means that magnetite, as well as non-absorbing particles (Martin, 1974b) could explain the polarization.

Table 5

HD	M/I	A_V^c/A_V^o
147889	0.42	0.025
147165	0.36	0.090
204827	0.16	0.027

The extinction in magnitudes produces by the polarizing grains in the visual band, A_V^c, has been computed in each case:

$$A_V^c\simeq1.08\sum_i\{20a_i^2n_i\bar{Q}_{Vi}\},\qquad i=1,2$$

where $\bar{Q}_{Vi}$ is an average efficiency factor for extinction in the V band, for grains of radius a_i.

A_V^c is compared with $A_V^o\simeq3E_{B-V}$ for each star in Table 5. It can be seen that the computed visual extinction is a very small fraction of the observed extinction A_V^o. The polarizing magnetite grains would not be responsible for the extinction in all three cases.

IV. Conclusions

The simple model proposed was able to illustrate some physical significance of the parameter k in Eq. (1) when computed separately for each star. It could show the change in the effective sizes of the grains along the line of sight. This result seems to be true when considering both dielectric or metallic grains.

The model is also consistent with both linear and circular polarizations observed in the line of sight of two stars with widely differing shapes of the linear polarization curve. It shows that magnetite, a ferromagnetic material, can be a constituent of the interstellar polarizing agents, though present polarization observations seems not to be good enough to conclusively determine the grain species. This situation will certainly improve when data in other wavelength ranges are available.

The required column densities for magnetite grains are below the cosmic abundance of iron available in the interstellar medium. This implies that a complete alignment of the particles is not necessary. On the other hand, the extinction yielded by such polarizing dust is quite small to reproduce the reddening observations. Other agents are required for the latter effect.

If a two clouds model is the way to explain the observational data for a relatively nearby star, such as σ Sco, the scale length of the galactic field irregularities should be smaller than that generally assumed.

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